Available online at www.sciencedirect.com

Resuscitation Plus

journal homepage: www.elsevier.com/locate/resuscitation-plus

Commentary and concepts

Exoskeletons as potential devices to support and enhance rescuers' chest compression performance during out-of-hospital cardiac arrest

Seamus Thierry[a,b,*], Cyran Le Guennec[c], Alexandre Le Falher[d,e], Lola Lauby[d,e], Laure Boyer[g], Lucia Vicente Martinez[g], Alexis Paillet[h], Willy Allegre[d,e,f]

Abstract

Exoskeletons are wearable structures that support and assist movement, or augment the capabilities of the human body. These functionalities could theoretically assist bystanders or rescuers performing manual chest compressions during out-of-hospital cardiac arrest, as this emergency procedure is prone to physical exhaustion. Compressions are an intense muscular effort involving a dynamic muscular pattern with conflicting postural constraints. Rescuer fatigue sets in rapidly, leading to postural instability and a lack of mechanical power delivered by the arms to the patient's torso, which affects hemodynamic efficiency.

Physical augmentation and postural stabilization are two functions that could be provided by an exoskeleton during cardiopulmonary resuscitation. This device would combine the advantages of manual and mechanical chest compressions, bypassing anthropometric parameters such as the rescuer's aerobic capacity and muscle mass to maintain efficient chest compressions, and avoiding the negative issues associated with over-assistance through a servomotor function. This concept paper examines the specifications of an ideal theoretical device in this context, noting the potential technical difficulties and barriers to implementation.

Keywords: Chest compressions, Active exoskeletons, Out-of-hospital cardiac arrest, Physical augmentation, Performance

Introduction

Exoskeletons may represent appealing valuable devices to mechanically assist, through a physical augmentation, manual chest compressions performed by bystanders during out-of-hospital cardiac arrest. This technology has shown to solve many constraints related to fatigue and exertion in repetitive industrial tasks, as they can compensate and increase human muscle strength and stabilize gait. To this day, a multitude of models are routinely used in the industrial field to prevent musculoskeletal disorders and reduce the risk of injuries to the back or shoulders during bending or lifting heavy loads, therefore improving comfort and productivity. Beside this human power augmentation function, exoskeletons can also serve haptic purposes and are present in the medical field, mostly in physical medicine for gait, lower and upper limb rehabilitation.[1]

These devices are divided into two categories: they can be either *passive* or *active*. Passive exoskeletons include shock absorbers, springs and elastics that store the energy harvested by the user's movement to maintain a posture or facilitate movement. Active exoskeletons, on the contrary, are electromechanical structures using an external drive (electric, pneumatic or hydraulic) to augment or strengthen a movement with a dynamic control and/or *retro*-control system. In this concept paper, we will evoke the potential eligibility and benefits of exoskeletons as devices for chest compression assistance during out-of-hospital cardiac arrest (OHCA).

Chest compression require mechanical power

In OHCA, chest compression are critical gestures mainly performed manually by bystanders or rescuers in a kneeling position, with the

* Corresponding author at: Anesthesiology Department, Groupe Hospitalier de Bretagne Sud, 56100 Lorient, France.
E-mail address: s.thierry@ghbs.bzh (S. Thierry).

https://doi.org/10.1016/j.resplu.2025.100871
Received 27 November 2024; Received in revised form 8 January 2025; Accepted 10 January 2025

patient lying on the floor. Despite their apparent simplicity[2] (immediate availability, adaptability to field conditions, no need for extra equipment), manual compressions are often ineffective and out of the objectives of ILCOR recommendations.[2,3] These pitfalls in the early phase of resuscitation directly influence the next links in the survival chain: when the chest is compressed too slowly, too rapidly, too much, too little, or with interruptions, probability of defibrillation success, return of spontaneous circulation, survival rates and favorable neurological outcomes are negatively affected.[4–8]

It is estimated that a rescuer has to deliver, for each compression and under the right angle, a mean force of 500 Newtons[9] to the chest to convert mechanical energy into a minimal efficient circulation. Failure to achieve such an intense effort can be related to three factors: the environment, the anthropometry of the patient and the cognitive and physical (muscular and aerobic performances) abilities of the rescuer. Chest compressions are repetitive, strenuous and stressful efforts that begin under temporal pressure and without warm-up. Clearly, rescuers with fitness and aerobic capacity (as provided by Emergency Medical Services (EMS)) are prone to more successful compliance with compression guidelines.[10,11] Nevertheless, even in trained populations, muscular performance follows a rapid (and nonlinear) decremental slope. Exertion is often unrecognized, suggesting that human factors and cognitive biases (e.g. surprise effect, affective considerations) may also influence the rescuer's representation of their own performance. Fatigue may affect compression rate, hand position, appropriate chest depth and overall positioning during CPR.[2] As guidelines state to switch operators every two minutes, in many circumstances CPR will be initiated by a lonesome bystander with no training and/or a lack of muscular / aerobic capabilities, waiting for emergency services without the possibility of substitution by another operator.

Chest compression require postural stabilization

From a biomechanical perspective, chest compressions represent a brutal effort and engage a complex and paradoxical interplay of a large number of muscular and joint functional units, with a strong need for sensorimotor coordination. The alternation of rapid compressions and decompressions shifts the rescuer's center of gravity, creating a conflict between the need for strong postural control, muscular cladding and the need of sufficient mobility in the rescuer's torso.[12] Therefore, chest compressions induce a complex muscular activity pattern for the rescuer with many areas endorsing a high mechanical load.

For example, the abdominal-lumbar region and back muscles are heavily engaged. Up to 1400 Newtons (N) are transmitted to intervertebral disks at each compression[13] to allow the arms to exert the greatest possible force to the patient's thorax via a vertical vector. In addition, some muscle groups, such as the *erector spinae*, are never at rest during the alternation of compression and decompression. Paraspinal muscles allow the rescuer's torso to return to the starting position during decompression, but they also have an agonistic, synergistic/co-contraction role during the push-down.[14] They reinforce and stabilize the rescuer's pelvis and lumbar spine during the compression phase by counteracting the action of the psoas muscle, which tends to exacerbate lobar lordosis. This stabilization functionality allows us to understand the high prevalence of back disorders among EMS rescuers for example, and why loss of postural during CPR leads to a lack of performance.[12]

Could exoskeletons assist muscular strength and postural during chest compressions?

The literature on the topic is scarce. We found only one article in the literature proposing to support chest compressions with a passive exoskeleton (none with an active skeleton). In one promising simulation study, rescuers wore a passive exoskeleton that was already commercially available and not dedicated to the specific task of chest compressions. The devices somehow improved back muscle activity and reduced back strain in both the thoracic and lumbar region.[15]

In the line with these concepts and results, we believe there is an area of research for engineers, doctors and designers to explore the potential benefits of transferring some of the rescuer's mechanical power to an exoskeleton. From a classification point of view, it would mean creating a new hybrid category between manual compression and mechanical devices (automated, such as the *LUCAS*™ or manual, such as the *Cardiopump*™).

Ideally, the device would be lightweight, readily available and easy to use, with an architecture that mimics human anatomy, allowing it to be used with little or no prior training. It would allow the user to apply adequate compression to the sternum without applying excessive force that could lead to visceral or skeletal damage, with servo control and modulation of compression force, depth and frequency, for example. Compression force variation during the procedure would also be controlled, as this is also an independent risk factor for chest injury. Any alteration in chest wall mechanics should be avoided as it will compromise optimal intrathoracic hemodynamics.[16]

In addition to providing muscular power to the upper limbs, the exoskeleton could also passively or actively support postural, thereby improving balance and preventing lumbar disorders in first responders.[17] If all these requirements can be met, the exoskeleton could combine the benefits of mechanical compression with a human-centered motor servo-control device, without the pitfalls of each category.

Expected difficulties in developing an exoskeleton dedicated to chest compressions

To date, we have identified many limitations that need to be investigated technically and clinically before such a device can be considered for chest compression support.

Issues related to the procedure

Chest compressions are a dynamic and cyclical movement that places a high mechanical load on several of the rescuer's joints for prolonged periods of time, especially in out-of-hospital cardiac arrest while waiting for emergency services to arrive. The rapid change between compression and decompression creates many conflicts regarding postural preservation.

As fatigue is known to occur rapidly in the arms [10], there is no data on which specific muscle group would benefit most from the exoskeleton. Attention should be paid to possible interference with accessory muscles, such as the paraspinal and pelvic muscles, which are also active at times during both the compression and decompression phases. Such interference could affect the user's postural and balance.

The device should not interfere with the decompression phase and allow the operator to regain the initial position to prepare for the next cycle. Decompression could also benefit from assistance, as the paraspinal and lumbar muscles are very active during this phase.

Loss of postural may be more progressive, the latter being independently responsible for insidious loss of strength [12]. Exoskeletons could theoretically prevent this postural instability over time by locking the operator's position and/or providing feedback regarding the correct angulation of the rescuer/patient pair.

On the patient side, it is interesting to note that the chest may also become softer after prolonged CPR, possibly reducing the need for mechanical support over time. This may be due to sternal fractures or softening of the costal cartilage due to cumulative pressure, thus changing the force required after prolonged CPR [18]. In conclusion, servo control would probably be essential to avoid under- or over-assistance, both of which are associated with poor results.

Issues related to the exoskeleton design

Without going into detail, the design of such a device would impose many constraints on engineers. Obviously, its structural design would have to be able to withstand the high mechanical load. It would also be necessary to decide whether the exoskeleton should be passive or active.

Passive exoskeletons offer significant advantages over active systems due to their simplicity, reliability, and comfort. Without the need for actuators or batteries, passive systems are lighter, less complex, and avoid the control challenges and safety risks of powered exoskeletons. In addition, passive exoskeletons prioritize user comfort and freedom of movement, making them ideal for dynamic tasks where agility is essential, such as in industrial or medical environments. In the literature, passive exoskeletons have been proposed as a way to address these issues by reducing the muscular effort associated with compressive movements and maintaining proper posture during physically demanding tasks.[19,20]

Active exoskeletons are more complex to develop. Power is an issue, especially for outdoor use. Preliminary calculations suggest a very demanding requirement of 100 or 200 Newton (to partially support the 500 N effort) for each compression.

Other considerations such as weight, actuators, joint flexibility, real-time modulation, adaptation to variations in user size, safety hazards and storage need to be taken into account.

By way of illustration, a recent prototype developed by our research team is shown in Fig. 1, with detailed specifications in Table 1.

The barrier of real-life implementation: The example of mechanical devices

Entrusting mechanical power to a machine to partially or totally execute chest compression is not new, but is historically half-hearted efficiency. Beyond primary efficacy, additional factors are to be considered and could possibly represent implementation pitfalls in the early chain of resuscitation. Influence of factors such as user's safety, time of installation, training, maintenance, storage for example can all together impair the initial benefits of any device. Exoskeletons should also not impair the operator's ability to switch and perform other tasks related to the resuscitation procedure.

Fig. 1 – Proof of Concept of hybrid exoskeleton for enhanced chest compression.

Regarding mechanical devices efficiency, implementation factors can partially explain the mismatch between favorable pre-clinical studies and large studies where benefits over manual compressions are clearly identified. Some studies show that mechanical compression devices can take a long time to be installed on the patient (several tens of seconds), during which time the patient no longer benefits from chest compressions. However, interruptions of compressions must be avoided at all costs during cardiopulmonary resuscitation because they reduce the survival rate and success rate of defibrillation.[6] This seems to be a critical implementation point for these tools, not to mention their weight (8 kg for the LUCAS-3).

A recent *meta*-analysis[21] confirmed that mechanical devices for chest compression also probably induced a higher incidence of over-assistance – compression related injuries (rib or sternal fractures, and sometimes life-threatening injuries such as pneumothorax or liver damage) compared to manual compressions. They also failed to show improvement in survival rates and good neurological outcomes.

As a consequence, the ILCOR and ERC 2021 Guidelines[22] did not recommend general use of automated mechanical chest compression devices but did suggest that such solution are a reasonable and valid alternative when sustained high-quality manual chest compressions are impractical or compromise. These situations can occur: in pre-hospital settings when cardiac massage is performed in cramped conditions (on board an ambulance or a helicopter for example) [23], in intra-hospital settings when access to the patient is difficult. (For example when the patient is installed for an invasive medical procedure where space is cluttered with heavy equipment (scanner, coronary angiography room). Use of these automated

Table 1 – Literature-based specifications for an exoskeleton dedicated to chest compressions assistance.

Criterion	Requirement	Reference
Ergonomics	Lightweight, user-friendly, quickly deployable, requiring minimal training	So BCL et al., 2020
Architecture	Human anatomy mimic for intuitive use	–
Compression Control	Servo-control of compression force, depth, and frequency	Gao et al, 2016
Force Variation Control	Control of compression force variation to reduce risk of ribcage injuries	Azeli et al., 2022
Muscle Activity Improvement	Reduce back load and improve muscle activity in thoracic and lumbar regions	So BCL et al., 2020
Lumbar Disorder Prevention	Passive or active support to enhance posture and balance	Jones and Lee, 2005
Hemodynamic Impact	Maintain optimal chest wall mechanics to prevent intrathoracic hemodynamic impairment	Azeli et al., 2022

mechanical devices is limited to specialized prehospital resuscitation teams or emergency medical services, as they require training, and maintenance. The development of an exoskeleton should avoid all these implementation barriers.

Conclusions

Effective manual chest compressions in out-of-hospital cardiac arrest require rescuers to deliver sufficient mechanical force and maintain posture for extended periods of time. Due to many factors, this goal is often not achieved and compromises the likelihood of a positive neurological outcome. Conceptually, the design and development of exoskeletons dedicated to this specific and repetitive effort could theoretically provide a valuable solution. The exoskeleton would assist the bystander through two functionalities: physical augmentation and dynamic posture stabilization. In addition, powered exoskeletons could provide force modulation and real-time monitoring of several key parameters of the procedure, such as the power delivered to the chest and the frequency, although these functions add complexity to the design. The prospect of an easy-to-use device could also enable people who are traditionally prone to rapid loss of efficacy due to fitness related factors (children, the elderly or disabled) to perform chest compressions.

However, there are many limitations and pitfalls in designing an ideal chest compression device due to the nature of chest compressions (high frequency, high mechanical load) and the diversity of potential users. Specifications should take into account the risk of under- and over-assistance provided by an exoskeleton, as well as the real-life implementation issues encountered with previous manual or automated chest compression devices.

Future technical and clinical studies are needed to draw conclusions about the potential benefits of implementing a device that has been shown to be effective in other human activities.

Funding source

The authors would like to thank the Groupe Hospitalier de Bretagne Sud and the Centre National d'Etudes Spatiales for their financial support.

Ethical statement

NA.

CRediT authorship contribution statement

Seamus Thierry: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Cyran Le Guennec:** Writing – review & editing, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alexandre Le Falher:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Lola Lauby:** Writing – review & editing, Validation, Supervision, Software, Methodology. **Laure Boyer:** Methodology, Investigation, Funding acquisition, Conceptualization. **Lucia Vicente Martinez:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Alexis Paillet:** Validation, Resources, Investigation, Conceptualization. **Willy Allegre:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

[a]Anesthesiology Department, Groupe Hospitalier de Bretagne Sud 56100 Lorient, France [b]Space Medicine Group, European Society of Aerospace Medicine, Germany [c]Université de Bretagne Sud, UMR CNRS 6027, IRDL F-56321 Lorient, France [d]Kerpape Rehabilitation Center 56270 Ploemeur, France [e]CoWork'HIT Innovation Center 56270 Ploemeur, France [f]Université de Bretagne-Sud, Lab-STICC, UMR CNRS 6285 56100 Lorient, France [g]Institut de Médecine et Physiologie Spatiale (MEDES) – Spaceship FR, BP 74404, 31405, Toulouse CEDEX 4, France [h]Centre National d'Études Spatiales (CNES) – Spaceship FR, 18 Avenue Edouard Belin 31400 Toulouse, France

REFERENCES

1. Anam K, Al-Jumaily AA. Active exoskeleton control systems : State of the art. Procedia Eng. 2012;41():988–94. https://doi.org/10.1016/j.proeng.2012.07.273.
2. Wik L. Quality of cardiopulmonary resuscitation during out-of-hospital cardiac arrest. JAMA 2005;293(3):299. https://doi.org/10.1001/jama.293.3.299.
3. Stiell IG, Brown SP, Christenson J, et al. What is the role of chest compression depth during out-of-hospital cardiac arrest resuscitation ? .. Crit. Care Med. 2012;40(4):1192–8. https://doi.org/10.1097/ccm.0b013e31823bc8bb.
4. Leary M, Abella BS. The challenge of CPR quality : Improvement in the real world. Resuscitation 2008;77(1):1–3. https://doi.org/10.1016/j.resuscitation.2008.02.005.
5. Abella BS, Sandbo N, Vassilatos P, et al. Chest compression rates during cardiopulmonary resuscitation are suboptimal. Circulation 2005;111(4):428–34. https://doi.org/10.1161/01.cir.0000153811.84257.59.
6. Edelson DP, Abella BS, Kramer-Johansen J, et al. Effects of compression depth and pre-shock pauses predict defibrillation failure during cardiac arrest. Resuscitation 2006;71(2):137–45. https://doi.org/10.1016/j.resuscitation.2006.04.008.
7. Nassar BS, Kerber R. Improving CPR performance. Chest J. 2017;152(5):1061–9. https://doi.org/10.1016/j.chest.2017.04.178.
8. Brouwer TF, Walker RG, Chapman FW, Koster RW. Association between chest compression interruptions and clinical outcomes of ventricular fibrillation out-of-hospital cardiac arrest. Circulation 2015;132(11):1030–7. https://doi.org/10.1161/circulationaha.115.014016.
9. Tomlinson AE, Nysaether J, Kramer-Johansen J, Steen PA, Dorph E. Compression force–depth relationship during out-of-hospital cardiopulmonary resuscitation. Resuscitation 2006;72(3):364–70. https://doi.org/10.1016/j.resuscitation.2006.07.017.
10. McDonald CH, Heggie J, Jones CM, Thorne CJ, Hulme J. Rescuer fatigue under the 2010 ERC guidelines, and its effect on cardiopulmonary resuscitation (CPR) performance. Emerg. Med. J. 2012;30(8):623–7. https://doi.org/10.1136/emermed-2012-201610.
11. Ochoa FJ, Ramalle-Gómara E, Lisa V, Saralegui I. The effect of rescuer fatigue on the quality of chest compressions. Resuscitation 1998;37(3):149–52. https://doi.org/10.1016/s0300-9572(98)00057-4.
12. Bucki B, Waniczek D, Michnik R, et al. The assessment of the kinematics of the rescuer in continuous chest compression during a 10-min simulation of cardiopulmonary resuscitation. Europ. J. Med. Res. 2019;24(1). https://doi.org/10.1186/s40001-019-0369-6.
13. Tsou JY, Chi CH, Hsu RMF, Wu HF, Su FC. Mechanical loading of the low back during cardiopulmonary resuscitation. Resuscitation 2009;80(10):1181–6. https://doi.org/10.1016/j.resuscitation.2009.06.025.
14. Tsou JY, Su FC, Tsao PC, et al. Electromyography activity of selected trunk muscles during cardiopulmonary resuscitation. Am. J. Emerg. Med. 2013;32(3):216–20. https://doi.org/10.1016/j.ajem.2013.10.044.
15. So BCL, Cheung HH, Liu SL, Tang CI, Tsoi TY, Wu CH. The effects of a passive exoskeleton on trunk muscle activity and perceived exertion for experienced auxiliary medical service providers in cardiopulmonary resuscitation chest compression. *Int. J. Ind. Ergon.*. 2020;76:102906. https://doi.org/10.1016/j.ergon.2020.102906.
16. Azeli Y, Barbería E, Fernández A, García-Vilana S, Bardají A, Hardig BM. Chest wall mechanics during mechanical chest compression and its relationship to CPR-related injuries and survival. *Resuscitation Plus*. 2022;10:100242. https://doi.org/10.1016/j.resplu.2022.100242.
17. Jones AYM, Lee RYW. Cardiopulmonary resuscitation and back injury in ambulance officers. *Int. Arch. Occup. Environ. Health*. 2005;78(4):332–6. https://doi.org/10.1007/s00420-004-0577-3.
18. Suazo M, Herrero J, Fortuny G, Puigjaner D, López JM. Biomechanical response of human rib cage to cardiopulmonary resuscitation maneuvers: Effects of the compression location. *Int J Numer Method Biomed Eng*. 2022;38(4)e3585. https://doi.org/10.1002/cnm.3585.
19. Toxiri S, Näf MB, Lazzaroni M, et al. Back-support exoskeletons for occupational use : an overview of technological advances and trends. IISE Transactions On Occupational Ergonomics And Human Factors. 2019;7(3–4):237–49. https://doi.org/10.1080/24725838.2019.1626303.
20. Kermavnar T, De Vries AW, De Looze MP, O'Sullivan LW. Effects of industrial back-support exoskeletons on body loading and user experience : an updated systematic review. Ergonomics. 2020;64(6):685–711. https://doi.org/10.1080/00140139.2020.1870162.
21. Gao Y, Sun T, Yuan D, et al. Safety of mechanical and manual chest compressions in cardiac arrest patients : A systematic review and meta-analysis. Resuscitation 2021;169:124–35. https://doi.org/10.1016/j.resuscitation.2021.10.028.
22. Wyckoff MH, Greif R, Morley PT, et al. 2022 International consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations : summary from the basic life support ; advanced life support ; pediatric life support ; neonatal life support ; education, implementation, and teams ; and first aid task forces. Circulation 2022;146(25). https://doi.org/10.1161/cir.0000000000001095.
23. Putzer G, Braun P, Zimmermann A, et al. LUCAS compared to manual cardiopulmonary resuscitation is more effective during helicopter rescue—a prospective, randomized, cross-over manikin study. Am. J. Emerg. Med. 2012;31(2):384–9. https://doi.org/10.1016/j.ajem.2012.07.018.